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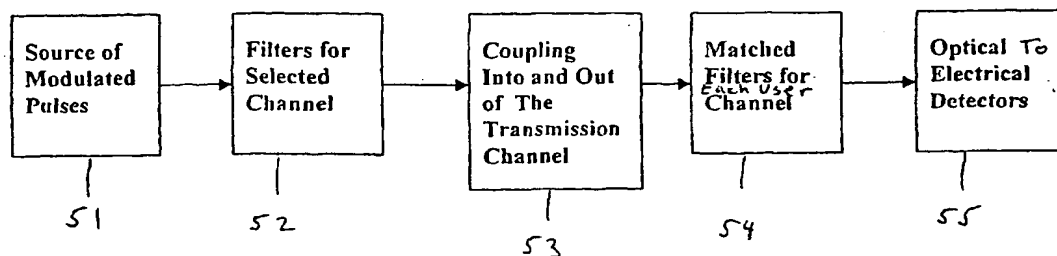
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(54) Title: ELECTROMAGNETIC MATCHED FILTER BASED MULTIPLE ACCESS COMMUNICATIONS SYSTEMS



(57) Abstract: An electromagnetic matched filter based multiple access communications system having a source of modulated pulses (51) from a digital data stream; an initial filter (52) which shapes the incoming modulated pulse into a desired pulse for transmission across the communication medium; a second filter (54), identical to the initial filter, which is matched to the pulse which exit the communications medium, a detector (55) which converts the modulated pulse stream into the original digital data stream, and signals which are designed with specific mathematical properties which make the system efficient and minimizes crosstalk between channels. The signals decay rapidly from the central lobe at a higher than  $1/x$  rate and zero points of the autocorrelation function having high order multiplicities. The type of system allows multiplexing of multiple data streams with much greater flexibility, robustness, and density.

WO 01/50663 A1

**PATENT APPLICATION**

**FOR**

**ELECTROMAGNETIC MATCHED FILTER BASED  
MULTIPLE ACCESS COMMUNICATIONS SYSTEMS**

ELECTROMAGNETIC MATCHED FILTER BASED  
MULTIPLE ACCESS COMMUNICATIONS SYSTEMS

5                                    CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit under Title 35 U.S.C. § 120 of United States Provision Application No. 60/173,882 filed on December 30, 1999.

10                    1. FIELD OF INVENTION

The present invention relates to all types of multiplexing and modulation communications systems. Examples of such systems include radio and optical communications in such communications media as wireless, copper, or fiber optics. The invention produces a series of signals that allow modulation and multiplexing at a density beyond the standards used today.

2. DESCRIPTION OF THE PRIOR ART

20                    Multiplexing and Demultiplexing:

The basic concept of a multiplexing system is the sending of multiple communication streams on the same line. A form of multiplexing is time-division multiplexing. This form of multiplexing allocates various sequential bits in a communication stream to different users. For instance the first, fifth, and ninth bits would be one user's bits, the second, sixth, and tenth a second user's bits, and so on. The transmitter or multiplexor knows what time slots to utilize when transmitting a user's information and the receiver or demultiplexor knows at what time slots the user's information will arrive.

30                    Wavelength division multiplexing (WDM) is a second type of multiplexing. WDM utilizes a different wavelength, or a corresponding

frequency, in order to separate different communication streams or users. Thus, in a communications system, one user would utilize a source which transmits a signal  $\sin(c_1 * t)$ , while another user would utilize a source which transmits a second signal  $\sin(c_2 * t)$ . The multiplexing is done by transmitting separate  
5 wavelengths. The demultiplexing is accomplished by separating the wavelengths at the receiver end.

An optical system can easily separate two frequencies, such as two colors of light on a fiber optic system. There are a number of methods to accomplish the goal of separating the frequencies. Spatial light separation of the frequencies  
10 is one method. This method uses a prism, optical grating, or other diffractive devices in order to separate the different frequencies. Another method to separate the frequencies uses dispersion in optical materials or filters, such as thin film filters, in-fiber gratings, or Bragg grating based filters. Such filters have no difficulty separating the two channels only as long as only one frequency is  
15 present in each of the two streams.

#### Modulation:

While individual wavelengths are easily separated by optical means, the  
20 individual wavelengths have to be modulated in order for there to be any information carried by the communication stream. The problem with the simplistic demultiplexing process described above flows from the fundamental tenet of communication that one frequency, transmitting alone, cannot transmit any information. The amount of information that can be transmitted is directly  
25 proportional to the bandwidth of the communication stream. Because the bandwidth of an individual frequency is 0, no information can be transmitted on that individual frequency. The key to the transmission of information is that the source, i.e. the  $\sin(c_1 t)$  source, must be modulated in order to transmit information. Perhaps the oldest form of modulation, which is equivalent to  
30 sending smoke signals, is on/off keying (OOK). This is the equivalent of sending a series of smoke signals, i.e. either the smoke goes up and is observed or it is

not. Similarly, in a modern digital communication system, the source is either turned on so that it transmits a signal to the end user, indicating a 1, or it is turned off, so that the end user receives no signal, indicating a 0. This allows a simple transmission of 0, 1 digital data.

5           The problem with modulating the transmitted signal, as above, is that the number of frequencies in the transmitted signal are greatly increased. This is necessary in order to transmit information, but it makes the separation of different multiplexed channels much more difficult. In the theoretical situation of the above referenced OOK, if the source is instantaneously turned on and  
10           instantaneously turned off, the resulting signal stream will have infinite bandwidth. It is well known that the frequency spectrum in this case shows the form  $\sin(x - f_1) / (x - f_1)$ , where  $f_1$  is the original frequency of the source. The difficulty of separating these types of signals, or channels, is well known. When the channels use overlapping portions of the frequency spectrum, simple  
15           prisms or corresponding material-based filters will not be able to efficiently separate the different communication streams.

          Another known method for modulating the communication source is called phase shift keying (PSK). In on/off keying (OOK), the 0's and 1's are literally transmitted on the waveform, i.e. either  $1 \times \sin(c_1 t)$  is transmitted or  $0 \times \sin(c_1 t) = 0$  is transmitted. In phase shift keying either  $1 \times \sin(c_1 t)$  is  
20           transmitted for a 1, or  $-1 \times \sin(c_1 t)$  is transmitted for the 0. While it might seem that the spectral problems of OOK are lessened in PSK, the reality is that the spectral problems of PSK are identical to those of OOK, as illustrated in Figure 1.

25

#### Electromagnetic Filtering:

          It is known that the nature of the materials from which electromagnetic filters are made causes the response of the material to light or other  
30           electromagnetic signals to depend upon the frequency of the signal impacting the material. Typical electromagnetic filtering can be accomplished with an in-fiber

grating, a Bragg grating, a thin film filter, a spatial light separation filter, or any filter which can independently alter the amplitude and frequency of individual frequencies. Different electromagnetic filters change the amplitude and phase of specific wavelengths in different ways. This filtering process is mathematically  
5 equivalent to a convolution filter. However, the impossibility of sampling instantaneously in time generally results in significant crosstalk between adjacent channels.

Accordingly, a new electromagnetic matched filter process with specially designed signals is needed that optimizes the process of matched filtering entirely  
10 via electromagnetic components.

### SUMMARY OF THE INVENTION

The invention introduces a method to produce mathematical signal designs for a communications system. It also introduces new mathematical signal  
15 designs to a communications system. The method and the designs provide new and far reaching advantages over conventional communications systems. These new advantages allow more of the bandwidth within the system to be used. A basic tool which is used to analyze a communications system is the autocorrelation function. This invention creates a new signal design and a device  
20 which more completely follow and execute two fundamental mathematical concepts in a communications system: 1) The autocorrelation function will decay rapidly from the central lobe, i.e. at a higher than  $1/x$  rate which is typical of a WDM system. 2) The zero points of the autocorrelation function are designed with high order zero multiplicities, greatly reducing crosstalk. This type of  
25 system allows multiplexing of multiple data streams with much greater flexibility, robustness, and density.

The method involves choosing a signal which is periodically orthogonal to its translates, determining a first autocorrelation function associated with the signal, determining the Fourier transform of the first autocorrelation function,  
30 forming a second autocorrelation function by convolving the first autocorrelation function with itself; determining the square root of the second autocorrelation function, and taking the inverse Fourier transform of the square root process.

The device consists of a filter made in accordance with the method described above.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

5           Figure 1 is a graph illustrating the problems with the prior art. It is a graph of the spectrum of two wavelength division multiplexing (WDM) channels depicting overlapping energy between the channels. It is also an illustration of the autocorrelation function for a standard WDM system.

10           Figure 2 is another graph illustrating the problems with the prior art. It is a graph further illustrating the crosstalk problems with a WDM system. It shows the crosstalk induced by one additional user.

          Figure 3 is a graph illustrating the achievement of a significant reduction in crosstalk energy achieved in accordance with the invention.

15           Figure 4 is a graph illustrating the double zero construction of the autocorrelation function of the communication system in accordance with the invention.

          Figure 5 is a block diagram illustrating how an embodiment of our invention is used as one of the components of one channel in a communications system

20           Figure 6 is a block diagram illustrating in more detail how an embodiment of our invention is used in a two channel communications system.

          Figure 7 is a block diagram illustrating how an embodiment of our invention is used in a global, complete communications system using an arbitrary number of channels.

25

### **DETAILED DESCRIPTION OF THE INVENTION**

          The present invention will be understood more fully from the detailed description given below and from accompanying drawings of preferred embodiments of the invention, which, however, should not be taken to limit the invention to a specific embodiment, but are for explanation and understanding only.

30

          As the number of frequencies in a transmitted signal are greatly increased

in order to transmit information, the task of separating the different multiplexed channels becomes much more difficult. The difficulty of separating these types of signals is illustrated in Figure 1. Referring now to Figure 1, graph 10, which plots frequency along the horizontal axis and amplitude along the vertical axis, illustrates the difficulty of separating two multiplexed WDM channels. Curve 11 illustrates a frequency spectrum of one channel and curve 12 illustrates a frequency spectrum of a separate channel. Because both channels use overlapping portions of the frequency spectrum, there is a great deal of overlapping energy between the channels illustrated in curve 11 and curve 12. The overlapping energy occurs, for example, in the areas bounded by curve segments 11a and 12a and curve segments 11b and 12b. This overlapping energy results in crosstalk between the channels in prior art systems. Simple prisms or other filters manufactured from other materials cannot efficiently separate the different communication streams in the channels.

When phase shift keying either transmits  $1 \times \sin(c_1 t)$  for a 1 or  $-1 \times \sin(c_1 t)$  for a 0, this simple change will allow the communication source to be on continuously and one might think that this would keep the spectrum from being spread as dramatically as is illustrated in Figure 1. However, the reality is that the phase changes, that is, the changes from 1 to -1, have the same effect on the spectrum and the same problems with the spectrum will occur as are illustrated in Figure 1.

Crosstalk in communication systems utilizing convolution filters can also be analyzed via the autocorrelation function. Orthogonality between channels is indicated by periodic zeros in the autocorrelation function. The problem with typical WDM channels is that while these zeros exist at the appropriate times, they are only instantaneous in time and frequency. In order to get adequate signal for each bit, however, the receiver must integrate the signal for a non-trivial amount of time. In addition, it is impossible to only sample one exact frequency. These two problems result in very significant crosstalk between adjacent channels.

These two problems are also illustrated in Figure 1. The sinc functions in Figure 1 are equivalent to the autocorrelation function for each channel. The



places where these functions are exactly zero signify the locations in frequency where there is no cross talk. Such zero points are shown, for example, at points 13 and 14 along the horizontal axis in Figure 1. A similar graph results when the horizontal axis is plotted as time. That is, there are very specific and  
5 instantaneous points in time where there is no cross talk. However, the uncertainty of sampling instantaneously in time and sampling exactly in frequency makes it necessary to space channels much farther apart than the theoretical bandwidth. In reality one must integrate in time, over a non-trivial portion of the frequency spectrum, so that the cross talk away from these  
10 theoretical points of zero cross talk will be felt by the system and will be very significant.

Another way to visualize the problems with crosstalk in a prior art WDM system is illustrated in Figure 2 which illustrates the autocorrelation function 20 in a WDM system. The graph 21 in Figure 2 plots time along the horizontal axis and amplitude along the vertical axis. Graph 21 for the WDM autocorrelation  
15 function 20 is, coincidentally, the same shape as the spectrum of the transmitted signals. The zeros of this autocorrelation function, for example points 21a and 21b, represent potential additional users, or additional bits in a bit stream. The area under the curve of this autocorrelation function around these zeros is  
20 equivalent to the amount of crosstalk energy in the system. The area of crosstalk is shown as the area under the curve between the two lines 22 and 23 in Figure 2. The area between the lines 22 and 23 illustrated in Figure 2 represents the crosstalk induced by one additional user. Each zero has corresponding crosstalk energy in a fixed finite region around each zero in Figure 2 similar to the  
25 crosstalk energy illustrated by lines 22 and 23. The area in all of the fixed finite regions under the curve around all of the zeros of the autocorrelation function represent the total crosstalk energy. The total crosstalk energy grows without bound as more channels are added. The integration time required to achieve acceptable signal to noise ratios dictates that orthogonal signals are not sufficient  
30 to completely eliminate crosstalk.

The invention described herein solves the above mentioned problems with

crosstalk by introducing signals to the system which are specifically designed to have favorable autocorrelation functions. The fundamental ideas of the invention center around the idea that instead of the autocorrelation function represented by Figure 2, an autocorrelation function such as that shown in Figure 3 must be  
5 created by adaptively designing the signals. This redesign of the signals that will propagate through the system greatly reduces crosstalk.

The invention introduces signals to the communication systems which induce a number of positive properties to the autocorrelation functions. Property (1) is that the autocorrelation function associated with the signals of our invention  
10 decay rapidly from the central lobe; i.e., at a higher than  $1/x$  rate which is typical of a WDM system. Property (2) is that the zero points of the autocorrelation function are designed with high order multiplicities, greatly reducing crosstalk.

Our method starts with any one of a wide variety of signals which are well known in the literature and operates on the known signals in ways which satisfy  
15 the above properties; i.e., Property (1) and Property (2). An example of a set of mathematical signals which produce an autocorrelation function with some of the mathematical properties described above has been introduced to the mathematical literature by R.R. Coifman and Y. Meyer, "Remarques sur l'analyse de Fourier a  
fenetre," *Compte rendus de l'Academie edes Sciences, seria I: Mathematique*,  
20 Vol. 312, 1991, pp. 259-261 and translated into English in "Local Sine and Cosine Bases of Coifman and Meyer and the Construction of Smooth Wavelets,"  
Pascal Auscher, Guido Weiss, and M. Victor Wickerhauser in "Wavelets: A  
tutorial in Theory and Application," C.K. Chui, editor, pp. 237-256, Academic  
Press, 1992 (hereinafter "Coifman and Meyer"). One embodiment of our  
25 invention applies the mathematical properties of Coifman and Meyers to communications systems.

When the mathematical properties of Coifman and Meyers are applied to communications systems, the signals, local trigonometric signals, achieve the autocorrelation function illustrated in Figure 3. The construction outlined in  
30 Coifman and Meyer provides for a window function  $w(f)$ , which is the basis for the signals. An examination of this window function reveals that its

autocorrelation function has periodic zeros. This implies that if the spectrum of the signal is the window function  $w(f)$ , then translates of those signals will be orthogonal, and have the autocorrelation function with the mathematical properties described above and illustrated in Figure 3. This is exactly what is  
5 needed for an efficient communications system: A basic signal which can periodically transmit bits with each of these transmitted bits being orthogonal to one another, and with an autocorrelation function such as that illustrated in Figure 3.

The construction of the window function  $w(f)$  in Coifman and Meyer  
10 provides another fundamental advantage for a communication system. The windows described in Coifman and Meyer allow one to overlap two windows,  $w_1(f)$  and  $w_2(f)$ , in a very special way. If the signals  $s_1(t)$  and  $s_2(t)$  have spectra which are essentially equivalent to  $w_1(f)$  and  $w_2(f)$  then the periodic translates of  $s_1(t)$  and  $s_2(t)$  will all be orthogonal to each other. Thus the autocorrelation  
15 function for the system will be similar to that in Figure 3, and the cross correlation function for the systems will also show similar characteristics, i.e. periodic zeros and rapid decay.

Thus this invention would utilize  $k$  different signals  $s_1(k) \dots s_k(t)$ , which have the mathematical characteristics outlined above. When these signals are  
20 transmitted at appropriate points in time, they will remain orthogonal in the communications system and allow for optical demultiplexing at the other end of the communications system. This allows one to pack the spectrum of a communications system with a series of signals which enables a full bandwidth, or a nearly full bandwidth, communications systems. The system we have  
25 invented uses this methodology.

Referring to Figure 3, graph 30 plots time along the horizontal axis and amplitude along the vertical axis and illustrates the achievement of a significant reduction in the crosstalk energy of the system. Curve 31 illustrates a frequency spectrum of one channel and curve 32 illustrates a frequency spectrum of a  
30 separate channel. The area between lines 33 and 34 and below curve 31 represents the crosstalk energy of a WDM system. The area under curve 32 represents the crosstalk in the system which our invention produces. The

application of Coifman and Meyers windows to communications systems lowers the crosstalk.

5 The area under curves 31 and 32 between lines 35 and 36 shows an even more dramatic result. There is still significant crosstalk energy generated by curve 31; but almost none under curve 32. The curves in Figure 3 show that adding additional channels to the system represented by curve 32 will not increase crosstalk in distant channels and will increase crosstalk only in neighboring channels. Figure 3 shows that the crosstalk is greatly lowered by applying the Coifman and Meyer mathematical properties to communications  
10 systems. Although there is still significant crosstalk energy generated by curve 31, there is almost none under curve 32. Therefore, adding additional channels to a communication system represented by curve 32 will not increase crosstalk in distant channels. It will only increase crosstalk in neighboring channels.

15 While the construction outlined in Coifman and Meyer accomplishes some of the mathematical goals outlined in this invention, it is only one of many mathematical constructions which accomplishes one of the mathematical goals of this invention. Other autocorrelation functions with similar favorable mathematical properties can also be used.

20 While the above described Coifman and Meyers windows will virtually eliminate crosstalk with a distant channel, they do not eliminate crosstalk with channels which are relatively close to an operating channel. They do not eliminate crosstalk in the near channels because the Coifman and Meyer frequency windows, and the corresponding signals, only satisfy Property (1) described above. A simple square window in frequency will not satisfy either of  
25 the above described properties. Therefore, these measures won't allow full bandwidth utilization of the system. As shown in Figure 3, the crosstalk from distant channels is very small, as illustrated by the area under curve 32 and between lines 34-34 and lines 35-36. Therefore, additional channels added to a system represented by curve 32 will not increase crosstalk in distant channels.  
30 However, the crosstalk from near channels, represented by the area under the curve 32 around the zeros close to midpoint 37 of Figure 3 is still very significant. Indeed, the crosstalk from the near channels is almost identical to

that of the original system shown in Figure 2.

To address the near channel cross talk problem, we use an autocorrelation function which is zero in a region around the orthogonality points, or zeros of the autocorrelation function by taking the windows described by Coifman and Meyer  
5 and convolving them. Fourier analysis shows that the resulting autocorrelation function will then be the square of the original autocorrelation function. An illustration of the mathematical properties of this type of autocorrelation function is shown in Figure 4.

Referring to Figure 4, graph 40 plots time along the horizontal axis and  
10 amplitude along the vertical axis. Curves 41 and 42 illustrate the frequency spectrums of two separate channels. Figure 4 illustrates double zeros in the autocorrelation function of the system. The fundamental mathematical idea illustrated by the autocorrelation function in Figure 4 is that the zeros of the autocorrelation function are not simple zeros. The multiplicity of each zero of the  
15 autocorrelation function in Figure 4 is 2. This invention allows one to create autocorrelation functions with arbitrary multiplicities of zeros.

In this construction of the system, the crosstalk of the near channels is significantly reduced. The area of crosstalk is illustrated as the area under curves  
20 41 and 42 between lines 43 and 44 which shows that the crosstalk of the near channels is reduced significantly. These significant improvements in near channel crosstalk over the signals outlined in Coifman and Meyer now make it feasible to utilize all of the channels associated with this autocorrelation function.

As noted above, the Coifman and Meyer frequency windows, and the  
25 corresponding signals, only satisfy Property (1) described above. A simple square window in frequency will not satisfy either of the properties. Our invention creates signals which satisfy both properties. The signal illustrated by curve 42 in Figure 4 is obtained in the following manner. The method described below can be programmed into software or any other machine readable device  
30 and operated on a processor or any similar device.

Let  $s(t)$  be a signal which is periodically orthogonal to its translates. Examples of such  $s(t)$  signals are sinc functions, appropriate signals whose

autocorrelation function is a Coifman & Meyer window, or any variety of wavelets at any individual scale. Each of these signals will satisfy Property (1). Since the periodic translates of these signals are orthogonal, there will be periodic zeros in the autocorrelation function associated

5 with  $s(t)$ .

A Fourier transform operation is then performed on  $s(t)$ . If we denote the Fourier transform of  $s(t)$  to be  $S(f)$ , then the Fourier transform of the autocorrelation function of  $s(t)$  is  $H(f) = |S(f)|^2$ . After obtaining the Fourier transform of the autocorrelation function of  $s(t)$ ,  $H(f)$ , we form a new  
10 autocorrelation function by convolving  $H(f)$  with itself to obtain  $G(f)$ , where  $G(f) = \text{Conv}(H(f), H(f))$  and where convolution is the standard convolution operation known in mathematics and signal processing. We then take the inverse Fourier transform of  $G(f)$  to obtain  $g(t)$  which is an autocorrelation function with periodic double zeros and the desired autocorrelation function.

15 The next step is recovering the signals which created  $g(t)$ . The recovery of the signals is performed by taking the square root of  $G(f)$ . That is, the new, recovered, signals will have the Fourier transforms  $S_2(f) = \sqrt{G(f)}$ . These new signals generate an autocorrelation function which satisfies Property (1) and Property (2) thereby generating an autocorrelation function similar to the one  
20 illustrated by curve 42 in Figure 4.

Finally, using the waveform which is created by  $\sqrt{G(f)} = S_2(f)$  and by determining the inverse Fourier transform of the result, a filter is designed which will produce the desired signals,  $s_2(t)$ , which will generate the above  
25 autocorrelation function  $g(t)$ .

One standard method for detecting the presence of a signal in a communications system, radar system, or image document is by matched filtering. The device consists primarily of four components and is shown in  
30 Figure 5. Figure 5 is a block diagram illustration of one channel 50 in a system we have introduced. When using matched filtering, the transmitted signal should be approximately known. In Figure 5, this is done through components 51 and 52

which transmit a modulated pulse and then filter the signal in order to adjust its shape to the desired signal. The first component 51 is a source of modulated pulses providing a source for a data stream. The source could be any type of system that supplies a data stream such as a diode laser, or other laser transmitter, any wireless transmitter, any fiber transmitter, or any source system that produces signals which are relatively stable in time, or with known variants.

The second component is a filter 52 for the selected channel signal. Filter 52 is designed in accordance with the method described above. The filters can be selected from any material or can be a mechanical filter which will produce the signal required by the method described above. The filters may be thin film filters, in-fiber gratings, fiber optic Bragg gratings, spatial light modulation filters, or any other filter which will alter the amplitude and phase of individual frequencies of the modulated pulses in order to produce the desired signal form.

Then, the signal is transmitted through a medium such a fiber optic cable or other communications channel. Block 53 is a device to couple the individual channel onto the transmission channel for the system. It couples the signal into and out of the transmission channel. It can be any coupling and transmission device such as a fiber optic branch line, copper wire, or coaxial cable. Finally, at the receiver end, a corresponding matched filter searches for the particular signal which was originally transmitted. Block 54 is a matched filter that is specifically designed for the specially designed signals. It is the same filter as block 52 and may be constructed of the same materials as the filter in block 52. Filter 54 may also compensate for the dispersive and absorptive properties of the transmission line. The final detectors, shown in block 55, are standard power only optical to electrical detectors as there is no need to detect the phase of the signal in this final detection.

It will be understood by those skilled in the art that the order of some of the components could be changed without changing the operation of the system and without the need to modify the filters in block 52 or in block 54. For example, filter 52 could come before or after modulator 51, in some systems.

Figure 6 illustrates an embodiment of a communications system 60

incorporating the invention. System 60 illustrates only two channels for simplicity. Any number of channels may be used. Although system 60 is an optical system, the invention can be applied to other communications systems with the appropriate changes in components. In Figure 6, Part I, 61, corresponds to block 51 in Figure 5; Part II, 62, corresponds to blocks 52, 53, and 54 in Figure 5. Part III, 63, corresponds to block 55 in Figure 5. Each channel in Part I, 61, has its own data source 61a and 61b. The data sources may be the same type, or may be different. They need only provide the type of signal frequency previously described with respect to block 51 in Figure 5, that is, a source of modulated pulses. The data streams from each of the data sources 61a and 61b are acted upon by laser transmitters 61c and 61d and then passed through time-frequency pulse shapers 61e and 61f which are equivalent to the filters for each channel. As in Figure 5, modulators 61a and 61b could be placed after filters 61e and 61f.

The data streams then enter Part II, 62, where they pass through filters 62a and 62b which are designed in accordance with the method described above. When the filtered data streams leave filters 62a and 62b, they pass through an optical coupler 62c to optical fiber 62d which transmits the data streams to a distant location, as far away as 100 km. When the data streams reach the distant location, they are passed through a power splitter 62e which divides the data streams into two channels and through matched filters 62f and 62g. As in Block 54 in Figure 5, matched filters 62f and 62g are specifically designed for the specially designed signals. They are the same filters as block 62a and may be constructed of the same materials as the filters in blocks 62a and 62b.

After the data streams pass through matched filters 62f and 62g, they pass to optical to electrical detectors in Part III, 63, which comprises a dense wavelength-division multiplexed system 63a and a digital oscilloscope with electrical-to-optical converter 63b.

Figure 7 illustrates a global embodiment 70 of the components of a complete communications system utilizing our invention, consisting of N channels. The sources of the modulated pulses, illustrated by diode lasers 70a, could be any type of system such as wireless or fiber which produces signals



which are relatively stable in time, or with known variants. The data streams from diode lasers 70a are shaped and modulated by time-frequency modulators 70b, via the filters manufactured in accordance with our method, into a digitally modulated series of electromagnetic pulses. These individual channels are then  
5 combined by couplers 70c and then coupled into one communication channel 70e by an optical coupler 70d. This channel could be a communications cable, such as a wire or fiber optic, or a particular spectrum in the air. At the destination, the single communication channel is acted upon by optical splitter 70f and transmitted to splitters 70g which divide the channel into the same number of  
10 channels as were initially generated by diode lasers 70a. From splitters 70g, optical-matched filters 70h separate each channel in accordance with our invention. If the channels were in the air, there will be no need for coupling and decoupling the individual channels. The filtered channels are then transmitted to optical to electrical detectors 70i.

15 The method of our invention can be programmed into software or any other machine readable device and operated on a processor or any similar device.

After the filter specifications for the signal are determined by using the method of our invention, the filter specifications are fed into a device which manufactures the desired filter. A good manufacturing process would be to burn  
20 the filter, using a laser, into the core of an optical communications fiber while it is being drawn. Other suitable and conventional manufacturing processes would be, for example, a thin film deposition process performed by an epitaxial growth device.

Accordingly, a customer who wants to transmit information determines its  
25 needs and prepares its design specifications. Programmed software analyzes the design specifications using the method described herein. The software, applying the methods and algorithms described herein, will design the individual filters for the various channels of the system. After the designs for the filters are created, the designs will be transferred to optical filter design tools which consists of software  
30 and hardware. The filter manufacturing machines may be, for example, thin films, in-fiber gratings, optical fiber Bragg gratings, or any other suitable optical filters. After the filters are manufactured, they will be placed in the

communications system as shown in Figures 5, 6, and 7.

5 While this invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, the preferred embodiments of the invention set forth herein are intended to be illustrative, not limiting. Various changes may be made without departing from the spirit and scope of the invention defined in the appended claims.

**We claim:**

1. A method for designing a filter for multiple access communications system which minimizes crosstalk between channels comprising the step of identifying signals having a property by which the autocorrelation function associated with said signals decay rapidly from the central lobe, that is, at a higher than  $1/x$  rate which is typical of a wavelength division multiplexing communications system.
2. A method of designing a filter for a multiple access communications system which minimizes crosstalk between channels comprising the step of identifying signals  $s_2(t)$  having a first property by which the autocorrelation function associated with said  $s_2(t)$  signals decay rapidly from the central lobe, that is, at a higher than  $1/x$  rate which is typical of a wavelength division multiplexing communications system and having a second property in which the zero points of the autocorrelations function have high order multiplicities.
3. The method of claim 2 further comprising the steps of:
  - (a) choosing a signal  $s(t)$  which is periodically orthogonal to its translates;
  - (b) determining a first autocorrelation function associated with  $s(t)$ ;
  - (c) denoting the Fourier transform of  $s(t)$  to be  $S(f)$ ;
  - (d) denoting the Fourier transform of said first autocorrelation function of  $s(t)$  as  $H(f)$ ;
  - (e) determining said Fourier transform,  $H(f)$ , of said first autocorrelation function of  $s(t)$  in accordance with the equation  $H(f) = |S(f)|^2$ ;
  - (f) forming the Fourier transform of a second autocorrelation function by convolving  $H(f)$  with itself;
  - (g) determining said convolution according to the equation  $G(f) = \text{Conv}(H(f), H(f))$ ;
  - (h) determining the square root of  $G(f)$ ;
  - (i) denoting said square root of  $G(f)$  as  $S_2(f)$ ; and
  - (j) taking the inverse Fourier transform of  $S_2(f)$ .

4. The method of claim 2 wherein  $s(t)$  is a sinc function.
5. The method of claim 2 wherein  $s(t)$  is a signal whose autocorrelation function is a Coifman Meyer window.
6. The method of claim 2 wherein  $s(t)$  is selected from any variety of wavelets at any individual scale.
7. The method of claim 2 wherein  $s(t)$  is any function whose translates are periodically orthogonal to  $s(t)$ .
8. A method of filtering a signal of a communications system which minimizes crosstalk between channels comprising the steps of:
  - (a) creating a signal from a source of modulated pulses;
  - (b) filtering said signal of modulated pulses with a filter designed in accordance with the method specified in claim 2;
  - (c) coupling said filtered modulated pulses onto the transmission channel for said communication system;
  - (d) receiving said coupled filtered modulated pulses from said transmission channel with a matched filter designed in accordance with the method specified in claim 2;
  - (e) detecting said signal from said matched filter.
9. The method of claim 8 wherein said source of modulated pulses produces signals which are relatively stable in time.
10. The method of claim 8 wherein said source of modulated pulses produces signals which have known variants.
11. The method of claim 8 wherein said filter is a fiber optic filter.
12. The method of claim 8 wherein said filter comprises in-fiber gratings.
13. The method of claim 8 wherein said filter comprises Bragg gratings.
14. The method of claim 8 wherein said filter comprises thin film filters.
15. The method of claim 8 wherein said filter comprises spatial light modulation filters.
16. The method of claim 8 wherein said matched filter searches for said signal that was originally transmitted.
17. The method of claim 8 wherein said filter is specifically designed for

said signals.

18. The method of claim 8 wherein said matched filter is specifically designed for said signal.

5 19. A method of filtering a signal of a communications system which minimizes crosstalk between channels comprising the steps of:

(a) creating a signal from a source of modulated pulses;

(b) filtering said signal of modulated pulses with a filter designed in accordance with the method specified in claim 6;

10 (c) coupling said filtered modulated pulses onto the transmission channel for said communication system;

(d) receiving said coupled filtered modulated pulses from said transmission channel with a matched filter designed in accordance with the method specified in claim 1;

15 (e) detecting said signal from said matched filter.

20 20. The method of claim 19 wherein said source of modulated pulses produces signals which are relatively stable in time.

21. The method of claim 19 wherein said source of modulated pulses produces signals which have known variants.

20 22. The method of claim 19 wherein said filter is a fiber optic filter.

23. The method of claim 19 wherein said filter comprises in-fiber gratings.

24. The method of claim 19 wherein said filter comprises Bragg gratings.

25. The method of claim 19 wherein said filter comprises thin film filters.

25 26. The method of claim 19 wherein said filter comprises spatial light modulation filters.

27. The method of claim 19 wherein said matched filter searches for said signal that was originally transmitted.

30 28. The method of claim 19 wherein said filter is specifically designed for said signals.

29. The method of claim 19 wherein said matched filter is specifically designed for said signal.

30. An electromagnetic matched filter based multiple access system for a communications system which minimizes crosstalk between channels comprising

- (a) a source of modulated pulses from a digital data stream;
- 5 (b) a first filter for shaping the modulated pulse into a desired pulse for transmission across the communication medium;
- (c) a transmission medium which is accurately modeled;
- (d) a second filter which is matched to the pulse which exits the communications medium; and
- 10 (e) a detector which converts the modulated pulse stream into the original digital data stream.

31. The electromagnetic matched filter based multiple access system of claim 30 wherein said first and second filters are identical.

32. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method  
15 specified in claim 2;

33. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method specified in claim 7.

20 34. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method specified in claim 2;

35. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method  
25 specified in claim 7.

36. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method specified in claim 3.

37. The electromagnetic matched filter based multiple access system of claim 30 wherein said first filter is designed in accordance with the method  
30 specified in claim 8.

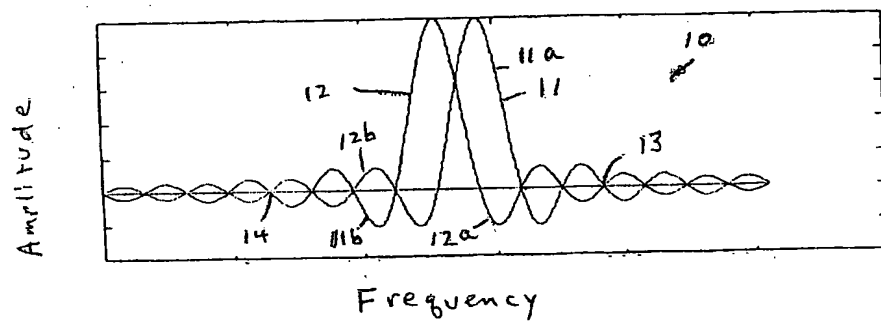


Figure 1:

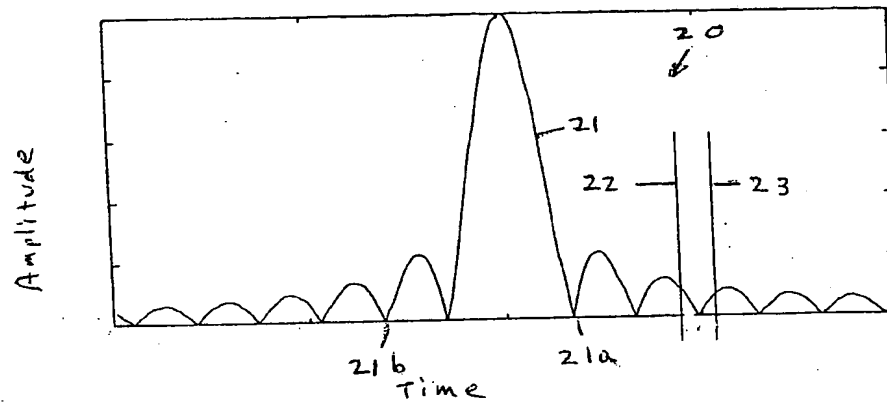


Figure 2:



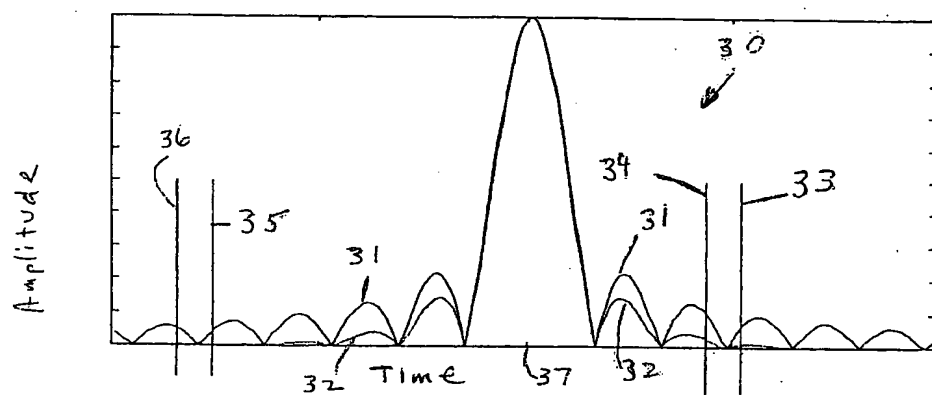


Figure 3

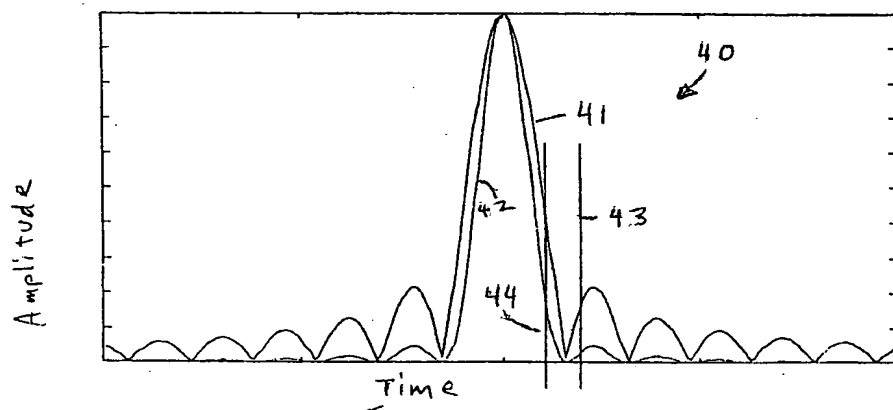
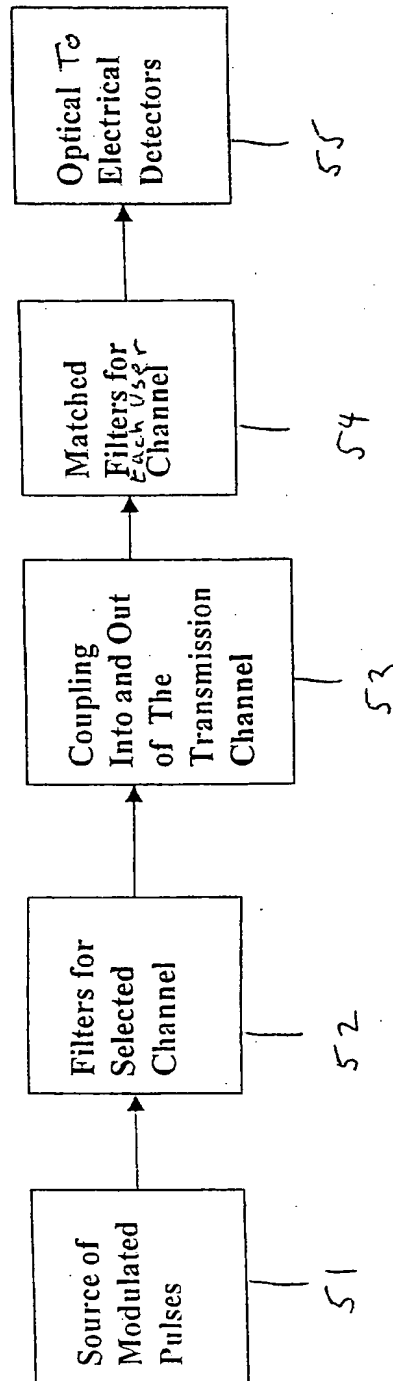


Figure 4:

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Figure 5



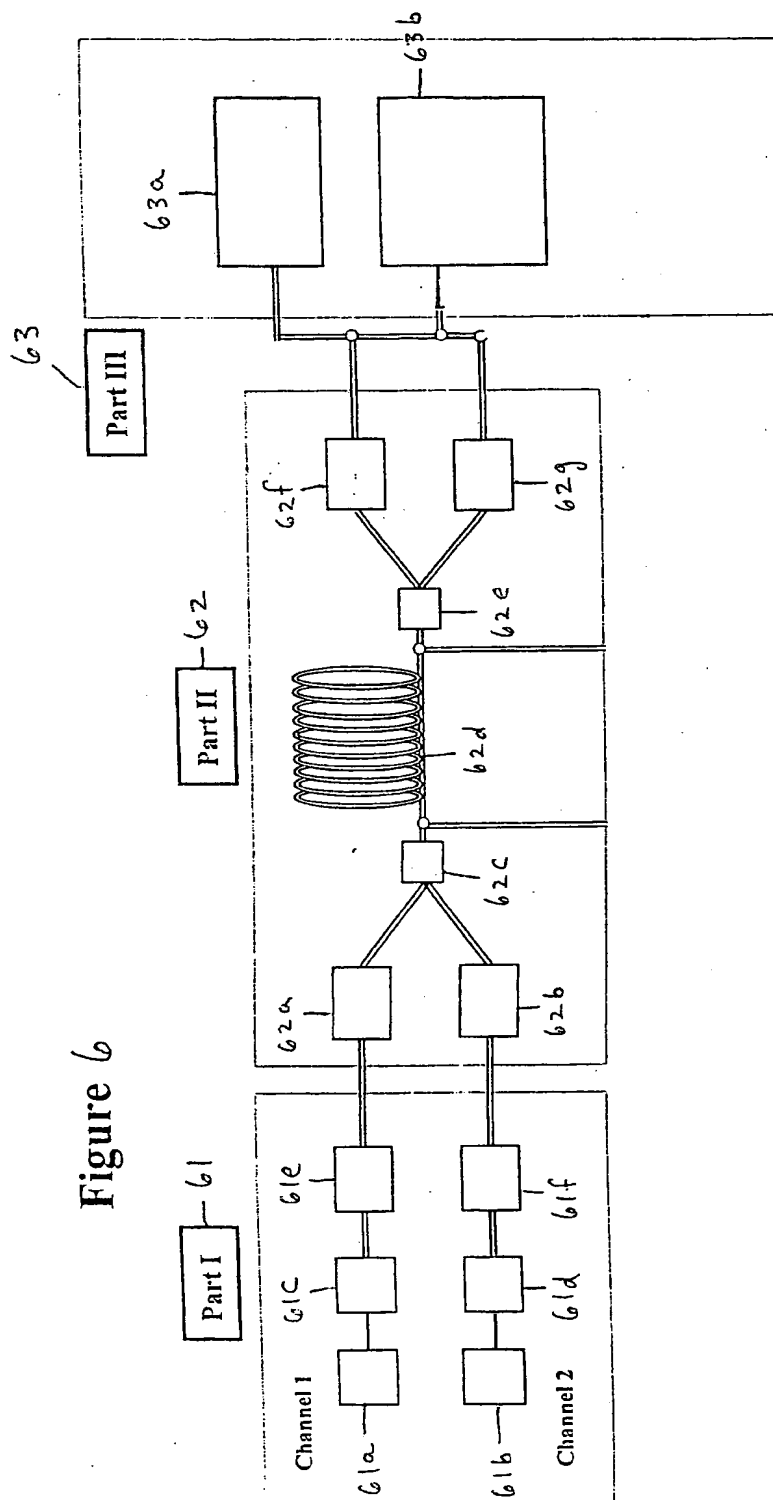


Figure 6

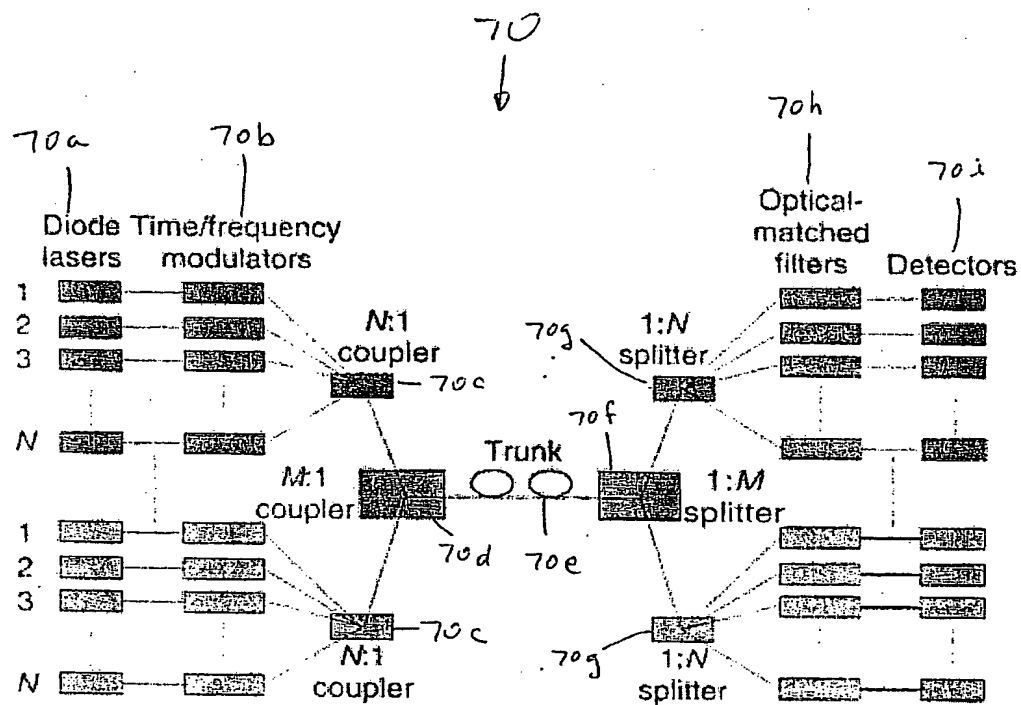


Figure 7

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US00/35570

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04J 14/02;  
US CL : 359/124, 127, 129

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
U.S. : 359/124, 127, 129, 173, 193

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
Please See Continuation Sheet

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,786,915 A (SCOBEEY) 28 July 1998 (28.07.1998), column 5, lines 30-68, column 6, lines 20-41.	1-37
Y	US 5,548,531 A (SHABEER) 20 August 1996 (20.08.1996), column 1, lines 35-54.	1-37
A	US 5,548,431 A (SHIN et al.) 20 August 1996 (20.08.1996), column 4, lines 21-43.	1-37
A	US 5,835,199 A (PHILLIPS et al.) 10 November 1998 (10.11.1998), abstract.	1-37

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

\* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent published on or after the international filing date
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- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

"T"

later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X"

document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y"

document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"

document member of the same patent family

Date of the actual completion of the international search

20 March 2001 (20.03.2001)

Date of mailing of the international search report

11 APR 2001

Name and mailing address of the ISA/US

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# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US00/35570

**Continuation of B. FIELDS SEARCHED Item3: EAST**

Word Search: wdm, filter, autocorrelation, crosstalk, four wave mixing (fwm).